

LA-UR-18-28896

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Title: Kilopower Space Reactor Launch Safety - Maximum Credible Fissions for a Criticality Accident

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Intended for: Report

Issued: 2018-09-19

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Kilopower Space Reactor Launch Safety Maximum Credible Fissions for a Criticality Accident

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Introduction

This note examines potential accident conditions for the Kilopower space reactor going critical during a launch accident. The goal of this analysis is to postulate the total number of fissions that could be generated during an accident event. The total number of fissions is an approximate surrogate for what will be the maximum release (or source term) for the accident. From the source term an approximation of dose (based upon the fission products generated and released) can be estimated. This note will only attempt to approximate the total number of fissions to the right order of magnitude. Dose consequences from the number of fissions will be documented in a separate note.

Scenario Description

The reactor fault conditions leading to a criticality have been postulated by several previous space reactor studies (for an example, see Weitzburg 1998.) From these studies, the most likely generic scenarios for a space reactor going critical during a launch involves the following potential issues:

1. The reactor being surrounded by a medium (such as water or wet sand) that increases moderation or reflection causing a criticality, or
2. The reactor core is deformed into a more favorable geometry causing criticality, or
3. The control mechanism being separated from the reactor by a blast or fire causing an insertion of reactivity, or
4. Some combination of these events.

One base assumption for scenario No. 1 involving the reactor surrounded by water is that the reactor survives the launch accident mostly intact and that the reactor falls onto land near water (say on a beach) such that the reactor is not always completely submerged, but instead is partially covered by the incoming tides. This is important since a reactor that is completely submerged in water may be critical but will not adversely impact the public given that any radiation will not be airborne but instead will be dispersed into the ocean.

Reactor criticality accidents typically are either short-term accidents or long-term accidents. A short-term accident is one where the reactor has a step insertion of reactivity (initial burst) and the reactor self-disassembles given the thermal shock. These accidents are on the order of milliseconds in length. A long-term accident is one where the reactor has an initial burst and survives the burst, followed by a longer period with the reactor critical or pulsing critical. Long-

term events can last days. The base cases for criticality events will be divided into two base cases, short-term and long-term events as follows:

The basic accident cases are as group as follows:

Base Case 1. Short-Term: Reactor has a step insertion of reactivity (initial burst) and the reactor self disassembles given the thermal shock. This event could be caused by:

- The control rod being ejected by a blast from a rocket explosion
- The control rod being ejected by impact with water or land
- The reactor is deformed into a geometry favorable for criticality, but self-destructs by initial burst.
- The reactor is immersed in water is further moderated or reflected and self-destructs by initial burst.

Base Case 2. Long-Term: Reactor has an initial burst followed by a longer period with the reactor critical or pulsing critical. This event could be caused by:

- Reactor survives the initial burst and settle into an equilibrium at temperature that keeps the k_{eff} at equilibrium. This might be the situation for a deformed reactor on land.
- Reactor survives the burst and the reactor pulses (critical and non-critical) as water moves in and out of the reactor. This could be the situation where the reactor lands on the shore and the tide comes in and out covering the reactor with water or the reactor is boiling away water fast enough to cause a pulsing effect.

Available Reference Material

Estimates of total number of fissions for criticality accidents have been the subject of numerous studies. For this paper, three primary reference documents are used and are:

1. Nuclear Regulatory Commission, "Nuclear Fuel Cycle Facility Accident Analysis Handbook," NUREG-CR-6410, May, 1998.
2. Department of Energy, "DOE Handbook - Airborne Release Fractions/Rates and Respirable Fractions For Nonreactor Nuclear Facilities," DOE-HDBK-3010-94 Vol. 1., December, 1994.
3. McLaughlin, T.P., et al. "A Review of Criticality Accidents," 2000 Revisions, LA-13638, Los Alamos National Laboratory, May, 2000.

The first two references are very important since they represent the current regulatory guidance from the NRC and DOE respectively. And they represent "reasonable conservative estimates" for criticality accidents. However, they are somewhat older and new data has been obtained since they were first published. McLaughlin 2000 is the most recent attempt to gather data for all of the known reactor criticality accidents. The DOE handbook was reaffirmed in 2013, but it is not clear if the criticality results were changed to reflect data from McLaughlin

2000. The McLaughlin 2000 review added several process criticality accidents that occurred after the NRC and DOE references were published and accidents previously not known in detail but when information was released after the opening of the Soviet Union. In addition, McLaughlin 2000 added a considerable amount of detail on each accident. McLaughlin 2000 is considered to be the most up to date reference on all criticality accidents to have occurred worldwide. It will be used as the primary reference for selecting values for the Kilopower space reactor.

Binning of Accidents

DOE Handbook 3010 is used as the basis for binning accidents into categories used in the reference material. DOE-HDBK-3010 has four basic categories for inadvertent criticality accidents:

- Solution criticality accidents (the most common type)
- Bare/Dry Solids criticality accidents
- Moderated/reflected solids (including moderation by liquids) criticality accidents
- Large storage arrays criticality accidents

For Base Case 1, a step insertion of reactivity, the most appropriate category is either a Bare/Dry Solid or Moderated/Reflected Solid. The Bare/Dry Solid bin is assigned to accidents involving control rod ejection by blast or impact and to deformation into a favorable geometry (and will be hence referred to as Base Case 1a.) The reactor immersed in water with disassembly will be assigned to Moderated/Reflected Solid (and hence called Case 1b.) Since all of these systems will involve only the initial burst and not a follow on critical condition, the total fission yield is only the burst yield.

For Base Case 2, an initial burst followed by a longer period where the reactor is critical, the case with a solid reactor staying critical will be assigned to Bare/Dry Solid bin (now called Case 2a). This would be the case for a reactor landing on land, deforming and going critical but not self-destruction. The case with a reactor going critical and then pulsing due to water will be assigned to Moderated/Reflected Solid (and now called Case 2b.)

The binning is summarized in Table 1.

Table 1. Binning of Accidents into Bins

Case	Description	Bin
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid
1b	Step insertion by water immersion	Moderated/reflected system
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system

DOE-HDBK-3010

Using bins from Table 1 and using the recommendations on initial burst yield and total fission from DOE-HDBK-3010 Vol 1 are shown in Table 2. The Bare/Dry Solid values are from pgs 6-15 to 6-16. The Moderated/Reflected Solid values are from pg. 6-15.

Table 2. Fission Yields by Accident Type – DOE-HDBK-3010

Case	Description	Bin	Initial burst yield	Total fission yield
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid	1E+17	
1b	Step insertion by water immersion	Moderated/reflected system	1E+18	
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	1E+17	1.E+18* (*estimated value)
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system	1E+18	1.E+19

NUREG-CR-6410

NUREG-CR-6410 makes estimates of fission yields for four types of configurations: 1) solution systems, 2) fully moderated/reflected solids, 3) powder systems and 4) large storage arrays. In the rule of thumb section solid metal systems are also included. Values for the fully moderated system are given on pg. 3-94. Values for the solid metal systems are presented on pg. 3-109. The primary sources of the data used as the basis for the values for moderated/reflected systems and bare/dry solid in NUREG/CR-6410 are from two references.

1. Olsen, A.R., G.O. Bright, V.O. Uotinen, C.L Brown et al., "Empirical Method for Estimating the Total Number of Fissions from Accidental Criticality in Uranium and Plutonium Systems," BNWL-1840, Pacific Northwest Laboratory, Richland, Washington, 1974.
2. Stratton, W.F., "A Review of Criticality Accidents," LA-361 1, Los Alamos National Laboratory, Los Alamos, New Mexico, 1967.

The binning of the data is shown in Table 3.

Table 3. Fission Yields by Accident Type – NUREG-CR-6410

Case	Description	Bin	Initial burst yield	Total fission yield
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid	1E+17	
1b	Step insertion by water immersion	Moderated/reflected system	1E+17	
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	1E+17	1.E+18
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system	1E+17	5.E+18

McLaughlin 2000

McLaughlin 2000 is the most “up to date” survey of the all criticality events that have occurred up to that point in time. There are not any additional process-based criticality accidents that the author is aware of since McLaughlin’s 2000 publication. McLaughlin’s work is reprinted in Table 4 below for both moderated/reflected systems and bare/dry solid systems. The table was examined and the information was used to assign values to the accident bins. The value selected was the typically the maximum applicable value for the scenario.

The following assignments were made based on the data from McLaughlin 2000 and reprinted in Table 4:

- Bare/Dry Solid Initial burst yield – Pg. 86, Livermore, CA, 26-03-63, 47 kg cylinder with Be reflector, severe fuel damage 3.7E17. Also, Pg. 89, Aberdeen, MD 6-09-68, 123 kgs of U-Mo unreflected, severe fuel damage 6.09E17. A value of 5E17 was chosen. This value is a higher value than both the recommended DOE and NRC values for Bare/Dry Solids
- Moderated/reflected system initial burst yield – Pg. 95, National Reactor Test Station, 22-07-54, 4.16 kg U(93) as U/Al alloy, Fuel/elements in water moderator, 4.68E18 rounded up to 5E18. Again, this value is a higher value than the DOE and NRC values.
- Bare/Dry Solid total fissions – Pg. 89, Sarov (Soviet Union), 17-06-97, ~44 kg U(90), Sphere with copper reflector, highly damped power oscillations lasting six days before termination, with 1E19 total fissions. The long-term fission total seems appropriate given the assumptions of a long-term criticality.

- Moderated/reflected system total fissions – Pg. 99, Kurchatov Institute, 26-05-71, U(20) O2 fuel rods, Be reflected in water, 2.E19 fission from approximately 50 pulses. Also pg. 95, Chalk River, 1950, which was 1.E20 fission which was also multiple excursions, but number of excursions was not specified. Data is lacking on the Chalk River event. Final assignment was 1E20 fissions. A long-term fission total seems appropriate for this long term criticality event.

Table 4 – Reprint of Table 11 of McLaughlin 2000
Reactor and Critical Experiment Accidents
Moderated/reflected and bare/dry solid only

Event	Date	Location	Material	Geometry	Damage	Total Fissions
<i>Bare and Reflected Metal Systems</i>						
1	21-08-45	Los Alamos, NM	6.2 kg δ -phase Pu	Sphere with WC reflector	None (one fatality)	$\sim 1 \times 10^{16}$
2	21-05-46	Los Alamos, NM	6.2 kg δ -phase Pu	Sphere with Be reflector	None (one fatality)	$\sim 3 \times 10^{15}$
3	1-02-51	Los Alamos, NM	62.9 kg U(93) metal	Cylinder and annulus in water	Minor	$\sim 1 \times 10^{17}$
4	18-04-52	Los Alamos, NM	92.4 kg U(93) metal	Cylinder, unreflected	None	1.5×10^{16}
5	9-04-53	Sarov, R.F.	~ 8 kg δ -phase Pu	Sphere with natural U reflector	Major core damage	$\sim 1 \times 10^{16}$
6	3-02-54	Los Alamos, NM	53 kg U(93) metal	Sphere, unreflected	Minor	5.6×10^{16}
7	12-02-57	Los Alamos, NM	54 kg U(93) metal	Sphere, unreflected	Severe	1.2×10^{17}
8	17-06-60	Los Alamos, NM	~ 51 kg U(93) metal	Cylinder with C reflector	Minor	6×10^{16}
9	10-11-61	Oak Ridge, TN	~ 75 kg U(93) metal	Paraffin reflected	None	$\sim 1 \times 10^{16}$
10	11-03-63	Sarov, R.F.	~ 17.35 kg δ -phase Pu	Sphere with LiD reflector	None	$\sim 5 \times 10^{15}$
11	26-03-63	Livermore, CA	47 kg U(93) metal	Cylinder with Be reflector	Severe	3.7×10^{17}
12	28-05-65	Whites Sands, NM	96 kg U(93)-Mo alloy	Cylinder, unreflected	Minor	1.5×10^{17}
13	5-04-68	Chelyabinsk-70, R.F.	47.7 kg U(93) metal	Sphere with natural U reflector	None (two fatalities)	6×10^{16}
14	6-09-68	Aberdeen, MD	123 kg U(93)-Mo alloy	Cylinder, unreflected	Severe	6.09×10^{17}
15	17-06-97	Sarov, R.F.	~ 44 kg U(90)	Sphere with copper reflector	None (one fatality)	$\sim 2 \times 10^{17}$ in one burst (total $\sim 10^{19}$)
<i>Moderated Metal and Oxide Systems</i>						
1	6-06-45	Los Alamos, NM	35.4 kg U(79.4) as $\frac{1}{2}$ -inch cubes	Water reflected pseudosphere	Minor	$\sim 4 \times 10^{16}$
2	~ 1950	Chalk River, Ontario, Canada	Aluminum-clad natural uranium	Rods in heavy water moderator	Minor	Unknown

3	2-06-52	Argonne National Lab, IL	U(93) oxide in plastic	Fuel elements in water moderator	Severe	1.22×10^{17}
4	12-12-52	Chalk River, Ontario, Canada	Natural uranium fuel rods	Heavy water moderated reactor	Severe	1.2×10^{20}
5	22-07-54	National Reactor Test Station, ID	4.16 kg U(93) as U/Al alloy	Fuel/elements in water moderator	Severe	4.68×10^{18}
6	15-10-58	Vinca, Yugoslavia	Natural uranium rods	Fuel rods in heavy water	None (one fatality)	$\sim 2.6 \times 10^{18}$
7	15-03-60	Saclay, France	2.2 tons U(1.5) as oxide	Fuel rods in water	None	3×10^{18}
8	3-01-61	Idaho Reactor Testing Area, ID	U(93) clad in aluminum	Fuel rods in water	Severe (three fatalities)	4.4×10^{18}
9	5-11-62	Idaho Reactor Testing Area, ID	U(93)/Al alloy plates, Al clad	Fuel elements in water	Severe	$\sim 1 \times 10^{18}$
10	30-12-65	Mol, Belgium	U(7) oxide	Rods in water/heavy water	None	$\sim 4 \times 10^{17}$
11	15-02-71	Kurchatov Institute	U(20) O ₂ fuel rods	Be reflected	None	2×10^{19}
12	26-05-71	Kurchatov Institute	U(90) O ₂ fuel rods	Water reflected	None (two fatalities)	2×10^{18}
13	23-09-83	Buenos Aires, Argentina	MTR type fuel elements	Pool type reactor	None (one fatality)	$\sim 4 \times 10^{17}$

From the data in Table 4, the bin values are estimated as follows for a Kilopower system in Table 5.

Table 5. Fission Yields by Accident Type based on McLaughlin 2000

Case	Description	Bin	Initial burst yield	Total fission yield
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid	5×10^{17}	
1b	Step insertion by water immersion	Moderated/reflected system	5×10^{18}	
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	5×10^{17} * (based on case 1a)	1×10^{19} * * 6-day excursion
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system	5×10^{18} * (based on case 2a)	1×10^{20} * * Long term excursion

Fission Yields Assigned to KiloPower

The easiest assignment of fission yields is to take the maximum from the three sources and use this as the assignment for KiloPower. The high values all come from McLaughlin 2000 shown in Table 5 and repeated in Table 6. This will be the final values used for launch accidents for KiloPower. These values are seen as the “maximum credible” values for a criticality accident.

Table 6. Fission Yields Assigned to KiloPower

Case	Description	Bin	Initial burst yield	Total fission yield
1a	Step insertion by rod ejection or geometry change	Bare/Dry Solid	5E+17	
1b	Step insertion by water immersion	Moderated/reflected system	5E+18	
2a	Initial burst followed by longer critical period caused by geometry change or partial rod withdrawal	Bare/Dry Solid	5E+17	1E+19* * 6-day excursion
2b	Initial burst followed by longer term pulsing reactor from water ingress	Moderated/reflected system	5E+18	1E+20* * Long term excursion

Comparison to KiloPower – KRUSTY Accident Values

The values in Table 6 can be compared to accident values for fission yield for the KiloPower space reactor concept that were performed for the accident analysis for the KRUSTY experiment. In McClure 2017, the number of fissions from a prompt burst of \$1.40 and subsequently disassemble the reactor core along with melting of the fuel would be approximately 3E+17 fissions. The conditions necessary to achieve this condition are unlikely and the probability of occurrence is considered extremely unlikely. This result is comparable to the initial burst yield for a Bare/Dry Solid shown in Case 1a of 5E17. As an additional note, this accident compares well to a LLNL accident of 1963 (p. 86 of McLaughlin 2000). Its fuel made an explosive sound, and it was observed as melting and burning. Its measured yield was 3.76E17 fissions.

The longer-term accident where the reactor runs for multiple days is approximately 3E19 fissions. Again, the conditions necessary for this result are considered beyond extremely unlikely in likelihood. This result is comparable to a total fission yield for a Bare/Dry Solid of 1E+19. In order to achieve the 1E19 result, the launch accident resulting in sustained criticality would have to last days before action is taken to shutdown the reaction. In addition, this result assumes the reactor is at the full operating power of 4 kW, which is probably not the case for this accident. The power produced during an accident criticality would be closer to that lost by

convection to the atmosphere and would be on the order of several hundred watts maximum. Therefore, a total fission yield of $1\text{E}+19$ is not unreasonable for Case 2a.

No moderated accidents were examined in McClure 2017.

Comparisons to Destructive Reactor Testing of Space Fission Reactors

Two different reactor systems were tested for similar types of reactivity insertion accidents including; 1) the Kiwi reactor designed as a ground test version of a thermal nuclear rocket and 2) the SNAP 10A reactor which was the first reactor flow in space. Each test is discussed below.

Kiwi-TNT

The Kiwi-TNT test is documented in King 1965. The Kiwi “Transient Nuclear Test” was designed to artificially insert the maximum reactivity possible into the Kiwi Reactor that was built and tested as part of the Rover program. This was accomplished by building control drum motors that spun at as fast a rate as was achievable, with the goal of inserting as much reactivity from the eight control drums as was possible. The test inserted ~ 7.3 dollars of reactivity into the reactor in a few milliseconds and achieved an initial burst yield of $1.3\text{E}20$ fissions.

This test is not applicable to Kilopower for several reasons. First, Kilopower does not have the excess reactivity that was present in the Kiwi reactors. Kilopower only has approximately ~ 2 dollars of excess reactivity. Second, this test did not represent accident conditions. The motor on the control drum were made especially for maximum speed and all eight motors turned together in unison. This is outside the failures one would equate to an accident condition. However, the test is interesting for the applicability of fission product release. This portion of the test will be of interest to Kilopower safety.

SNAPTRAN

The SNAPTRAN tests were also used to examine reactivity insertion accidents for the SNAP 10-A reactor. Three tests were performed for SNAPTRAN: 1) a series of non-destructive reactivity insertion events; 2) a maximum reactivity insertion event (like Kiwi-TNT) where the drums were spun at a very fast rate; and 3) a water immersion test that caused the reactor to go prompt critical. The tests are documented in Johnson 1966 and Kessler 1965. The first SNAPTRAN test is not of interest to this study. The second SNAPTRAN test was an insertion of ~ 5 dollars using a method similar to Kiwi-TNT. This test is also not of interest to Kilopower for reason similar to Kiwi-TNT in that it has more excess reactivity than Kilopower and does not represent accident conditions (i.e. artificially fast drums turning in unison.)

SNAPTRAN-3 is of interest to Kilopower. The SNAP 10A reactor was not designed to “not” go critical in water. The SNAP reactor was very critical in water and in the SNAPTRAN-3 test, water caused the reactor to be ~ 3.60 dollars in excess above delayed critical. This caused an initial burst of $1.2\text{E}18$ fissions. However, Kilopower is designed to “not” go critical in water and

should be sub-critical when submerged. But the accident conditions for this accident are very similar to data for a moderated/reflected systems analyzed in the tables. It is very similar to the value of 5E18 for an initial burst yield for water emersion. So, the SNAPTRAN results do reflect and provide more reassurance that the accident values assigned in this note are good “bounding” values for criticality accidents.

References

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